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**STUDY OF THE $\Delta^{++}(1232)$ INCLUSIVE
NEUTRINOPRODUCTION ON PROTONS AND NEUTRONS**

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Abstract

For the first time, the total yield and inclusive spectra of the $\Delta^{++}(1232)$ isobar are measured in νp and νn charged-current interactions. An indication is obtained that the $\Delta^{++}(1232)$ production mainly results from the neutrino scattering on the valence d -quark of the target nucleon. The total yield of $\Delta^{++}(1232)$ in νp interactions is compatible with that measured in hadronic interactions of the same net charge and net baryonic number. The yield of $\Delta^{++}(1232)$ in νn interactions is significantly suppressed as compared to the case of the proton target. The form of the squared transverse momentum distributions, both in νp and νn interactions, is found to be compatible with the available data on the neutrino production of Λ hyperon. The experimental data are compared with the LEPTO6.5 model predictions.

1. INTRODUCTION

Hadron resonances play a prominent role in the multiparticle production processes. In particular, they are important ingredients in the fragmentation of lepton-produced quark strings. The experimental data on the resonance production are necessary for a better understanding of the hadron formation space-time pattern. At present, more or less detailed experimental data on the inclusive lepton production are collected for mesonic resonances (see [1] and references therein for the case of the neutrino production), while the data on the total and differential yields of non-strange baryon resonances are obtained only for the $\Delta^{++}(1236)$ isobar production in muon-proton scattering [2].

The purpose of this paper is to obtain, for the first time, the data on the total and partial yields and the differential spectra of the $\Delta^{++}(1232)$ isobar in charged-current νp and νn interactions. The experimental procedure is described in Section 2. Section 3 presents the experimental results. Section 4 is devoted to the comparison of the experimental data with the predictions of the LEPTO6.5 Monte-Carlo event generator. The results are summarized in Section 5.

2. EXPERIMENTAL PROCEDURE

The experiment was performed with SKAT bubble chamber [3], exposed to a wideband neutrino beam obtained with a 70 GeV primary protons from the Serpukhov accelerator. The chamber was filled with a propane-freon mixture containing 87 vol% propane (C_3H_8) and 13 vol% freon (CF_3Br) with the percentage of nuclei H:C:F:Br = 67.9:26.8:4.0:1.3 %. A 20 kG uniform magnetic field was provided within the operating chamber volume.

Charged-current interactions containing a negative muon with momentum $p_\mu > 0.5$ GeV/c were selected. The overwhelming part of protons with momentum below 0.6 GeV/c and a fraction of protons with momentum 0.6-0.85 GeV/c were identified by their stopping in the chamber. Stopping π^+ mesons were identified by their $\pi^+ - \mu^+ - e^+$ decay. A fraction of low-momentum ($p_{\pi^+} < 0.5$ GeV/c) π^+ mesons were identified by the mass-dependent fit provided that the χ^2 -value for the pion hypothesis was significantly smaller as compared to that for proton. Non-identified positively charged hadrons are assigned the pion mass or, in the cases explained below, the proton mass. It was required the errors in measuring the momenta be less than 24% for muon, 60% for other charged particles and V^0 's (corresponding to strange particles) and less than 100% for photons. The mean relative error ($\Delta p/p$) in the momentum measurement for muons, pions, protons and gammas was, respectively, 3%, 6.5%, 10% and 19%. Each event was given a weight to correct for the fraction of events excluded due to improperly reconstruction. More details concerning the experimental procedure, in particular, the reconstruction of the neutrino energy E_ν , can be found in our previous publications [4, 5].

The events with $3 < E_\nu < 30$ GeV were accepted, provided that they satisfy the following topological and kinematic criteria for quasinucleon interactions: the net charge of secondary hadrons was equal to +1 (for quasinucleon interactions) or +2 (for quasinucleon interactions); the number of recorded baryons (these included identified protons and Λ hyperons, along with neutrons that suffered a secondary interaction in the chamber) was forbidden to exceed unity, baryons flying in the backward hemisphere being required to be absent among them; the effective target mass $M_t < 1.2$ GeV/c², the M_t being defined as $M_t = \sum (E_i - p_i^L)$ where the summation was performed over the energies E_i and the longitudinal momenta p_i^L (along the neutrino direction) of all recorded secondary particles. A detailed motivation of the aforementioned selection criteria can be found in [6] and references therein.

The numbers of accepted events corresponding to neutrino-proton and neutrino-neutron interactions are equal to 1839 and 2393, with the mean values of the neutrino energy $\langle E_\nu \rangle = 8.9$ and 8.7 GeV, respectively. Only in a small fraction of these events (23.7% in νp and 16.3% in νn interactions) an identified proton ($n_p^{id} = 1$) was present. In the remaining events (with $n_p^{id} = 0$) the proton hypothesis was applied to a non-identified positively charged hadron (if any) provided

that the proton hypothesis was not rejected by the momentum-range relation in the propane-freon mixture. This hypothetical proton, after introduction of a proper correction for its momentum, was combined with an accompanying positively charged hadron (an identified π^+ or a non-identified hadron) to compose a hypothetical π^+p combination. The most part of such combinations, especially in events containing two or more unidentified hadrons ($n_h^{nid} \geq 2$), is expected to be spurious due to the proton misidentification. As a result, the angular distribution of a 'proton' in the pion-'proton' rest frame turns out to be strongly shifted towards the negative values of $\cos \vartheta_p^*$, where ϑ_p^* is the angle between the 'proton' direction and the direction of the Lorentz boost from the lab system to the pion-'proton' rest system. As it has been shown by simulations based on the LERTO6.5 Monte-Carlo generator[7], the $\cos \vartheta_p^*$ distribution for the case of spurious π^+p combinations is strongly peaked at $\cos \vartheta_p^* \approx -1$ and rapidly falls with increasing $\cos \vartheta_p^*$ up to $\cos \vartheta_p^* \sim -0.6$, then begins flatten and becomes almost uniform at $\cos \vartheta_p^* > 0$. In order to reduce the share of spurious combinations in the experimental π^+p effective mass distribution for events with $n_p^{id} = 0$ and $n_h^{nid} \geq 2$, a cut $\cos \vartheta_p^* > -0.6$ was applied for the combinations of two unidentified hadrons, while those with $-0.6 < \cos \vartheta_p^* < 0$ a weight were ascribed, so that the total numbers of combinations with $\cos \vartheta_p^* < 0$ and $\cos \vartheta_p^* > 0$ (including those for events with $n_p^{id} = 1$ or $n_h^{nid} < 2$) turned out to be equal in the $\Delta^{++}(1236)$ peak region of $1.16 < m_{\pi+p} < 1.32$ GeV/ c^2 . This procedure, as it will be discussed in the next section, enables to improve the signal to background ratio in the $\Delta^{++}(1236)$ peak region and somewhat decreases the errors in the determination of its yield.

3. EXPERIMENTAL RESULTS

The π^+p effective mass distributions for νp and νn interactions are plotted in Figure 1. They can be described by the sum of a Breit-Wigner function [8], smeared according to the experimental resolution, and a background distribution $BG(m)$ parametrized as (following [2])

$$BG(m) = B \cdot q^\alpha \cdot \exp(-\beta m^\alpha) \quad ,$$

where B, α, β and γ are free parameters and q is the pion momentum in the π^+p rest frame.

The fit results in the following mean yields of $\Delta^{++}(1232)$: $\langle n \rangle_{\nu p} = 0.181 \pm 0.025$ and $\langle n \rangle_{\nu n} = 0.051 \pm 0.012$. The quoted errors here and below reflect also the uncertainty related to the choice of initial values of the fit parameters. We also analyzed our data without any elimination of combinations of two unidentified hadrons and observed a worsening of the signal to background ratio resulting in a smaller values and larger relative errors of $\langle n \rangle_{\nu p}$ and $\langle n \rangle_{\nu n}$ which turned out to be 0.164 ± 0.030 and 0.029 ± 0.018 , respectively. We have also tested the consistency of our data with the partial yield of $\Delta^{++}(1232)$ in νp interactions measured in [9] where only π^+p combinations with an identified proton with momentum less than 1 GeV/ c were used. In our experiment this partial yield turns out to be $\langle n(p_p < 1 \text{ GeV}/c) \rangle_{\nu p} = 0.103 \pm 0.012$ when a restriction on $\cos \vartheta_p^*$ (described in the previous section) was applied and $\langle n(p_p < 1 \text{ GeV}/c) \rangle_{\nu p} = 0.095 \pm 0.015$ when not. These values are quite compatible with the value of 0.105 ± 0.017 obtained in [9].

Table 1 presents the mean yields in different ranges of the neutrino energy and the Bjorken x_B variable. The quoted yields are normalized to the number of events of the corresponding subsample.

As it is seen, the yield of $\Delta^{++}(1232)$ at $x_B > 0.2$ exceeds that at $x_B < 0.2$, indicating that in its production the dominant role belongs to the neutrino scattering on the valence quark (in this case – on the valence d - quark) of the target nucleon. This feature, being less expressed, was observed earlier in deep-inelastic μp scattering [2]. The yield $\langle n \rangle_{\nu n}$ exhibits a strong dependence on E_ν (in particular, no Δ^{++} production is observed in the low-energy range of $3 < E_\nu < 7$ GeV). On the contrary, the yield $\langle n \rangle_{\nu p}$ is almost independent of E_ν . As it is seen from Figure 2, the yield $\langle n \rangle_{\nu p}$ is within error compatible with that measured in hadronic interactions with the same net charge (+2) and baryonic number (+1) in the final state (see [10, 11] and references therein).

We also attempted to measure the inclusive spectra of $\Delta^{++}(1232)$ on its kinematic variables: the Feynman x_F variable, the squared transverse momentum p_T^2 (where p_T is defined respective to

Table 1: The dependence of $\langle n \rangle_{\nu p}$ and $\langle n \rangle_{\nu n}$ on E_ν and x_B .

The range of variable	$\langle n \rangle_{\nu p}$	$\langle n \rangle_{\nu n}$
$3 < E_\nu < 7$ GeV	0.208 ± 0.036	0.013 ± 0.017
$7 < E_\nu < 30$ GeV	0.179 ± 0.037	0.072 ± 0.027
$x_B < 0.2$	0.153 ± 0.040	0.025 ± 0.024
$x_B > 0.2$	0.227 ± 0.035	0.052 ± 0.018

the intermediate boson direction), and the z variable – the fraction of the exchanged boson energy transferred to the $\Delta^{++}(1232)$ and defined as $z = (E - m_p)/\nu$, where E is the Δ^{++} total energy, m_p is the proton mass and ν is the exchanged boson energy $\nu = E_\nu - E_{\mu^-}$. Since these variables are senseless for the exclusive reaction $\nu p \rightarrow \mu^- p \pi^+$ (being fixed by definition: $x_F = 0$, $p_T = 0$, $z = 1$), the events-candidates to the latter were below excluded from consideration (see [12] for details).

Figure 3 shows the $\pi^+ p$ effective mass distributions for the full range of x_F , as well as for the $\pi^+ p$ system produced in the backward ($x_F < 0$) and forward ($x_F > 0$) hemispheres of the neutrino-produced hadronic system. The corresponding mean yields of $\Delta^{++}(1232)$ in νp and νn interactions are presented in Table 2, together with the data obtained in μp interactions [2].

Table 2: The $\Delta^{++}(1232)$ mean yields in different ranges of x_F in νp , νn and μp interactions.

	νp	νn	μp [2]
all x_F	0.170 ± 0.029	0.051 ± 0.012	0.10 ± 0.02
$x_F < 0$	0.101 ± 0.023	0.043 ± 0.011	0.08 ± 0.02
$x_F > 0$	0.057 ± 0.018	0.010 ± 0.009	0.02 ± 0.02

As it is seen, the yield of $\Delta^{++}(1232)$ for the case of the neutron target is approximately threefold suppressed as compared to the case of the proton target. This suppression is yet more expressed in the forward hemisphere ($x_F > 0$). It is interesting to note, that the magnitude of the yield of $\Delta^{++}(1232)$ in μp interactions occupies an intermediate position between those in νp and νn interactions. The forward-backward asymmetry parameter, defined as $A = (\langle n(x_F > 0) \rangle - \langle n(x_F < 0) \rangle) / (\langle n(x_F > 0) \rangle + \langle n(x_F < 0) \rangle)$, is equal to $A(\nu p) = -0.28 \pm 0.18$ and $A(\nu n) = -0.62 \pm 0.29$ for νp and νn interactions, respectively. These values can be compared with $A(\mu p) = -0.60 \pm 0.33$ in μp interactions [2], as well as with the value of $A_\Lambda = -0.589 \pm 0.004$ measured in the neutrino-production of Λ hyperons at higher energies, $\langle E_\nu \rangle = 45.3$ GeV [13].

The differential spectra of the $\Delta^{++}(1232)$ inclusive production versus variables z , x_F and p_T^2 are plotted in Figures 4 and 5. As it is seen from Figure 4, the z -distribution for νp interactions is rather flat, while the yield of the leading $\Delta^{++}(1232)$ (with $z > 0.5$) in νn interactions is strongly suppressed. A similar suppression is also observed at $x_F > 0$ in the x_F -distribution (Figure 5, the left panel), both for νn and μp interactions. On the other hand, the general trends of the x_F distributions in νp and μp interactions are almost the same in the backward hemisphere ($x_F < 0$). The p_T^2 distributions, both for νp and νn interactions, can be described by an exponential function with compatible slope parameters $b(\nu p) = 4.4 \pm 0.8$ and $b(\nu n) = 4.4 \pm 0.9$ (GeV/c) $^{-2}$, respectively (see the solid and dashed lines in Figure 5, the right panel). These values are compatible with those obtained for the neutrino-production of Λ (see [13, 14] and references therein). On the contrary, the data for μp interactions [2] (also plotted in Figure 5) can be satisfactorily described by a sum of two exponential functions with the slope parameters $b_1(\mu p) = 11.6 \pm 5.7$ and $b_2(\mu p) = 1.9 \pm 0.7$

(GeV/c) $^{-2}$ (see the dotted curve in Figure 5). As it was shown in [2], the high-momentum tail of the p_T^2 distribution can be described in the framework of the Lund string model [15] modified according to the QCD effects. The role of the latter in the high- p_T region increases with increasing W (see [16], as well as [17] and references therein) and is expected to be more prominent in the high- W region ($4 < W < 20$ GeV) at which the data [2] on the $\Delta^{++}(1232)$ muonoproduction are obtained.

4. COMPARISON WITH LEPTO6.5 MODEL PREDICTIONS

In this section we compare our data on the $\Delta^{++}(1232)$ yield in νp and νn interactions with the predictions of the LEPTO6.5 Monte-Carlo event generator for deep inelastic lepton-nucleon scattering [7]. Since the model puts a restriction $W > 2$ GeV on the invariant mass of the leptonproduced hadron system, the same should be done in the analysis of the experimental data. Figure 6 shows the π^+p effective mass distributions for νp and νn interactions at $W > 2$ GeV. The corresponding inferred total yields, as well as those at restricted x_B - ranges and the differential yields at $x_F < 0$ and $x_F > 0$ are quoted in Tables 3 and 4, along with the data on μp interactions [2] and the LEPTO6.5 predictions at the default values of the model parameters (except those related to the experimental restrictions on the kinematic variables).

As it is seen, the model predictions are within error compatible with the data for νn and μp interactions. It should be pointed out, that the $\Delta^{++}(1232)$ production in νn interactions at our energies is practically possible only owing to the diquark splitting in the target neutron remnant. The 'popcorn' [18] scheme of this splitting incorporated into the model qualitatively reproduces our data on νn interactions presented in Tables 3 and 4.

Table 3: The $\Delta^{++}(1232)$ total yields for three ranges of the variable x_B in νp and νn interactions at $2 < W < 7$ GeV and in μp interactions at $4 < W < 20$ GeV compared to the LEPTO6.5 model predictions.

Interaction	Experiment	Prediction
νp		
all x_B	0.133 ± 0.032	0.417
$x_B < 0.2$	0.090 ± 0.041	0.391
$x_B > 0.2$	0.150 ± 0.044	0.416
νn		
all x_B	0.068 ± 0.026	0.080
$x_B < 0.2$	0.036 ± 0.028	0.073
$x_B > 0.2$	0.098 ± 0.039	0.082
μp		
all x_B	0.10 ± 0.02	0.108
$x_B < 0.1$	0.09 ± 0.02	0.125
$0.1 < x_B < 0.2$	0.10 ± 0.02	0.115
$x_B > 0.2$	0.13 ± 0.03	0.091

As for the $\Delta^{++}(1232)$ production on the proton target, the model predictions badly overestimate (by about three times) the total and differential yields quoted in Tables 3 and 4. We failed to reach a satisfactory and simultaneous description of the experimental data presented in Tables 3 and 4 by a unique set of the model input parameters.

Table 4: The $\Delta^{++}(1232)$ differential yields at $x_F < 0$ and $x_F > 0$ in νp and νn interactions at $2 < W < 7$ GeV and in μp interactions at $4 < W < 20$ GeV compared to the LEPTO6.5 model predictions.

Interaction	Experiment	Prediction
νp		
$x_F < 0$	0.084 ± 0.025	0.240
$x_F > 0$	0.054 ± 0.017	0.177
νn		
$x_F < 0$	0.056 ± 0.018	0.041
$x_F > 0$	0.016 ± 0.014	0.039
μp		
$x_F < 0$	0.08 ± 0.02	0.089
$x_F > 0$	0.02 ± 0.02	0.019

5. SUMMARY

First experimental data on the total yield and inclusive spectra of $\Delta^{++}(1232)$ in νp and νn interactions are obtained. The total yield of $\Delta^{++}(1232)$ in νp interactions is compatible with that measured in hadronic interactions of the same net charge and net baryonic number. The yield of $\Delta^{++}(1232)$ at $x_B > 0.2$ exceeds noticeably that at $x_B < 0.2$, indicating that the neutrino scattering on the valence d -quark of the target proton or neutron plays a dominant role in the $\Delta^{++}(1232)$ production process. The $\Delta^{++}(1232)$ yield for the case of the neutron target is significantly suppressed as compared to the case of the proton target. This suppression is more expressed in the forward hemisphere ($x_F > 0$), as well as for the leading $\Delta^{++}(1232)$ with $z > 0.5$. The p_T^2 distributions can be described by an exponential function with slope parameters $b(\nu p) = 4.4 \pm 0.8$ and $b(\nu n) = 4.4 \pm 0.9$ (GeV/c) $^{-2}$ which are compatible with those for Λ hyperon in neutrino-induced reactions. The LEPTO6.5 model predictions agree with the measured $\Delta^{++}(1232)$ total yield at $W > 2$ GeV for νn interactions, but overestimate by about 3 times that for νp interactions.

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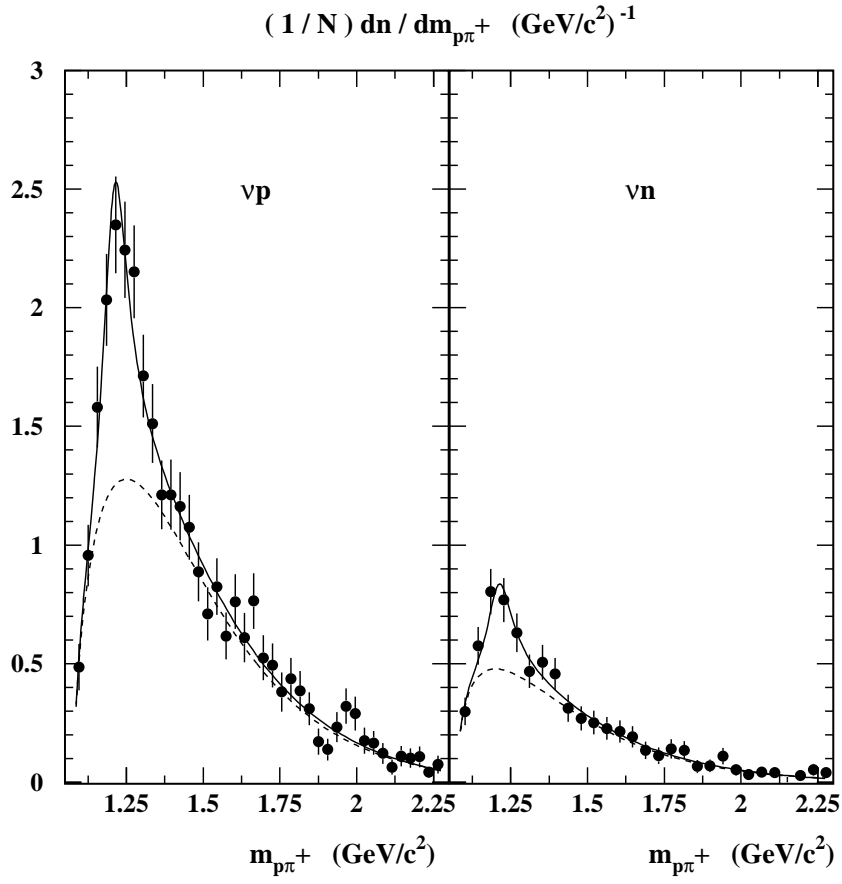


Figure 1: The π^+p effective mass distributions in νp and νn interactions. The curves are the fit result (the background distribution is shown by dashed curves).

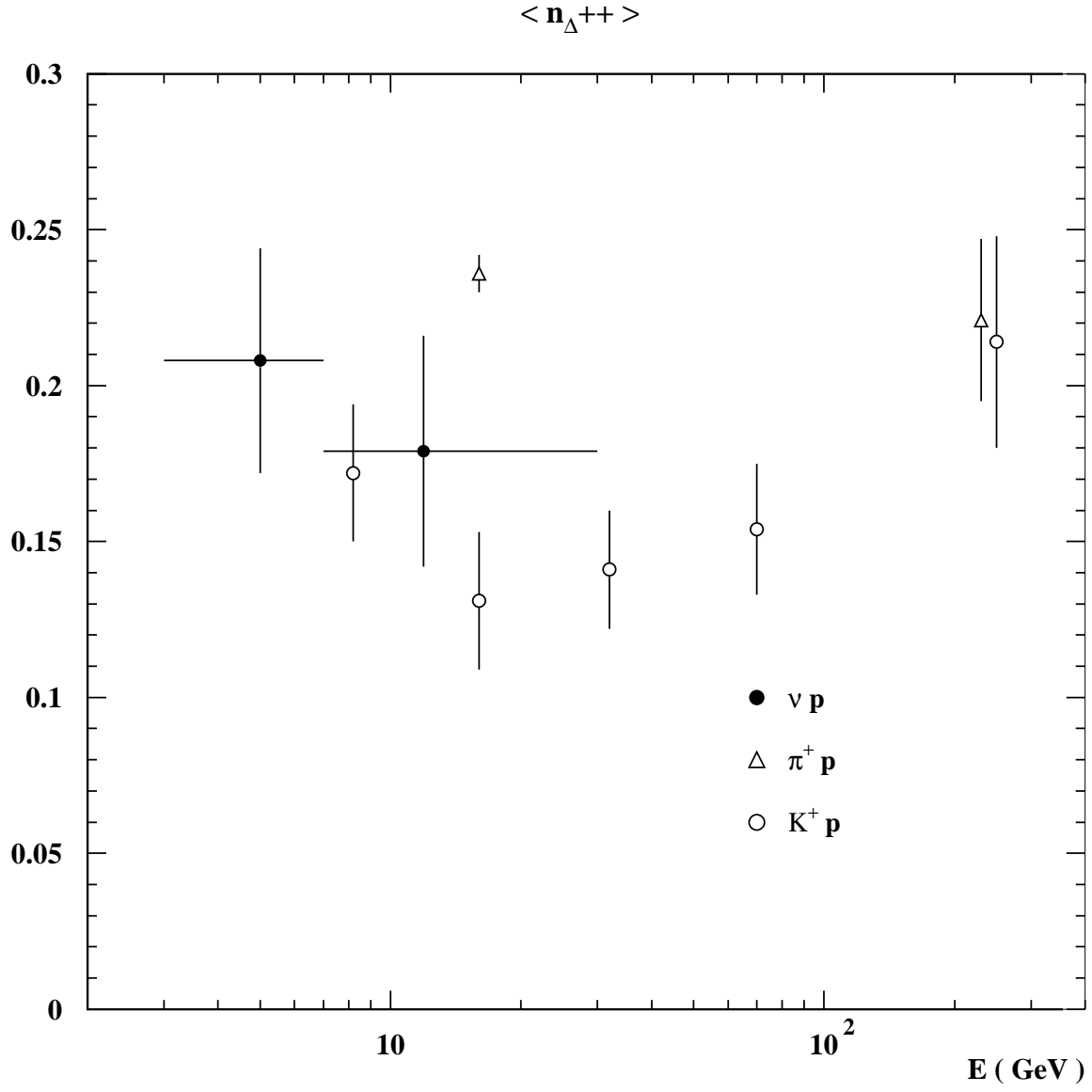


Figure 2: The incident energy dependence of the $\Delta^{++}(1232)$ mean yield in νp , $\pi^+ p$ and $K^+ p$ interactions.

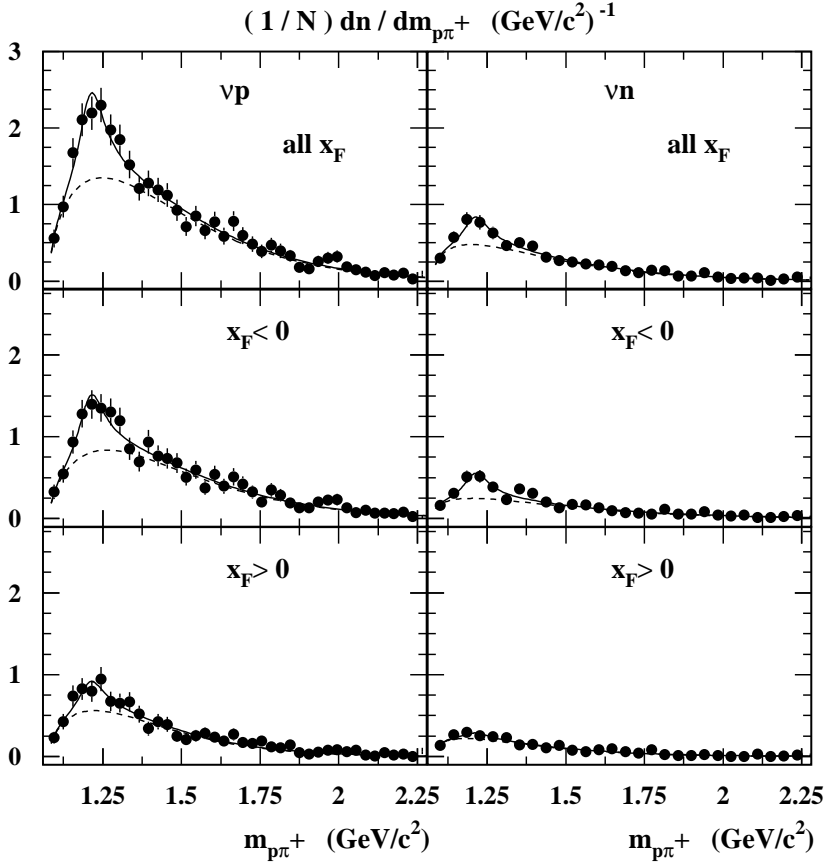


Figure 3: The π^+p effective mass distributions in νp and νn interactions for three different ranges of x_F . The events-candidates to the reaction $\nu p \rightarrow \mu^- p \pi^+$ are excluded. The meaning of curves is the same as for Figure 1.

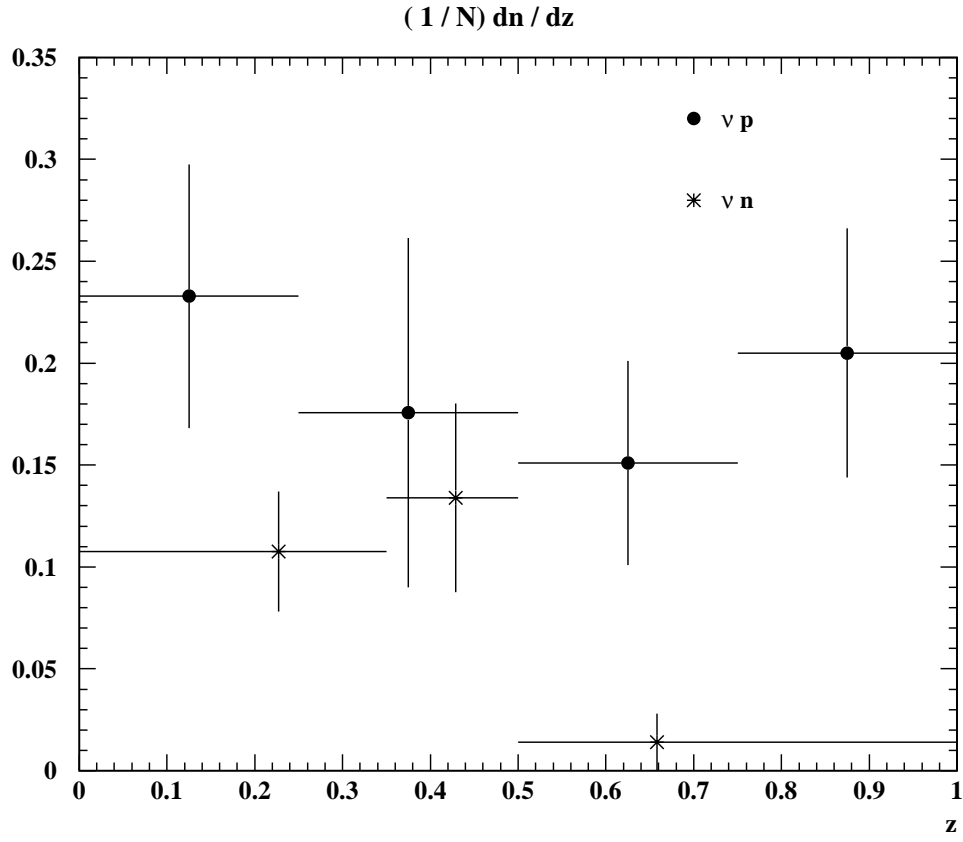


Figure 4: The differential spectra of $\Delta^{++}(1232)$ on the z variable in νp and νn interactions.

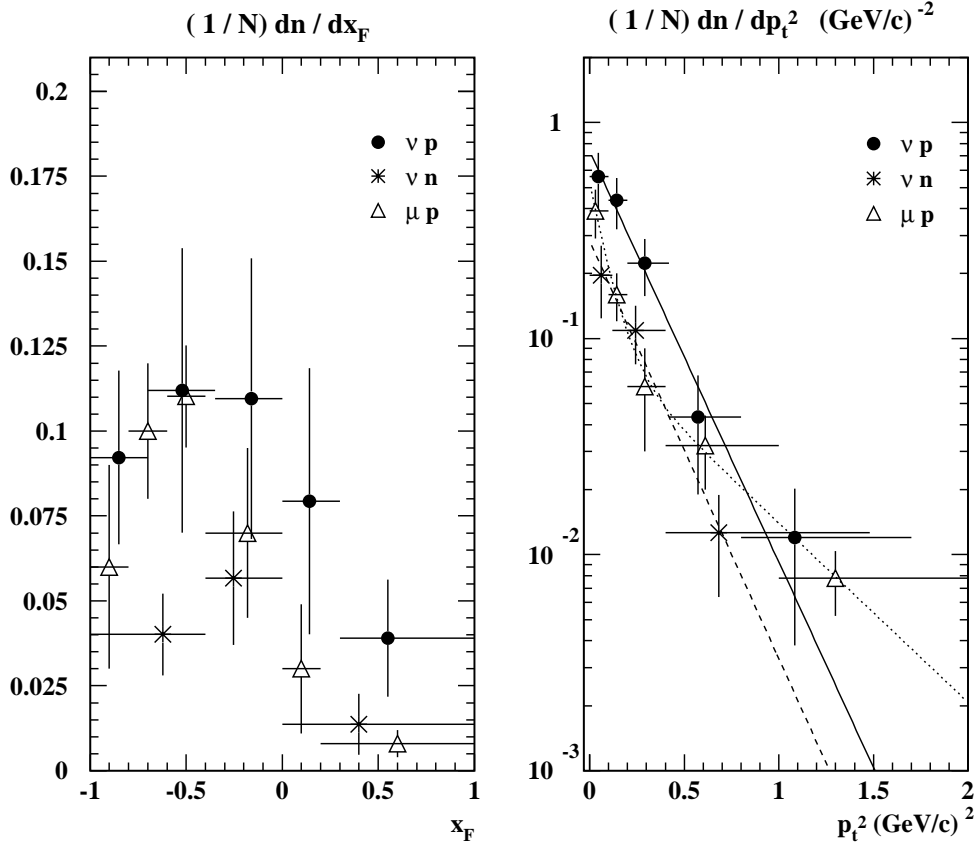


Figure 5: The differential spectra of $\Delta^{++}(1232)$ on x_F and p_T^2 variables in νp , νn and μp interactions. The curves are the fit result (see the text).

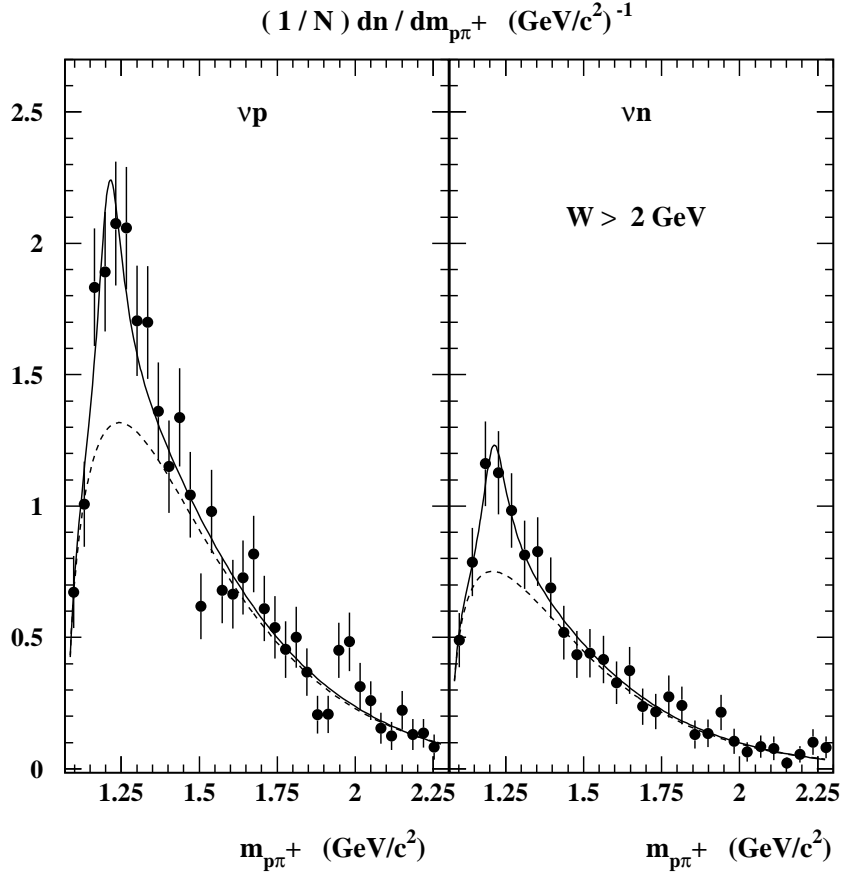


Figure 6: The π^+p effective mass distributions in νp and νn interactions at $W > 2 \text{ GeV}$. The meaning of curves is the same as for Figure 1.